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Selecting Method for Number of Slots and Poles in Brushless Direct Current Motor

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Abstract

Cogging torque is produced by the magnetic interaction between the stator core and the permanent magnet attached to the rotor. If we use the fractional slot winding, we can decrease cogging torque. In this paper, we propose a method to select number of poles and number of slots reasonably so as to satisfy the three technical requirements (the number of slots of unit winding per phase must be integer, the three-phase symmetric situation must be satisfied, the number of slots per pole per phase must be larger than 0.25.) and two economical requirements (coil pitch factor must be larger than 0.5, winding factor must be larger than 0.85.) of Brushless DC motor. We also propose a method to select a number of poles and a number of slots so that the goodness coefficient is small and the periodic coefficient is large to decrease cogging torque.

Keywords

Brushless Direct Current Motor (BLDC Motor), Fractional Slot winding, Cogging Torque

1. Introduction

Brushless DC motor is broadly used in the economy, defense industry, and in the field of information industry, due to its simple structure, easy manufacturing, and high performance. A brushless DC Motor is a kind of typical PM electric machine. Cogging torque is one of the important problems in the design of PM electric machines.

So, we have to pay attention to the decrease of cogging torque in BLDC Motor design [1, 3-5]. For the winding of BLDC Motor, fractional slot winding is often used because of two main reasons [7, 9], First, the cogging torque is decreased [2, 6, 8, 10, 11, 13]. Second, we can increase the number of poles even if the number of slots is small [12, 14].

Figure 1 shows the structure of PM electric machines that use fractional slot winding, slotless and toothless winding, and lap winding, respectively. Fractional slot (a), the interaction between stator and rotor being canceled, makes less cogging torque than lap winding (c). In the case of slotless and toothless structures (Figure 1b), a larger amount of Permanent Magnet is used because of the increase of air gap, while cogging torque is not generated.

For example, in the case of Ns=3, m=3, we can select the number of poles up to Np=4. When the pole number increases, the yokes of the stator and rotor become lower, consequently, the inner diameter of the stator and outer diameter of the stator get smaller. The moment of rotor inertia is proportional to the biquadratic rotor diameter, thus moment inertia is decreased, resulting in much improvement of responsivity, one of the important indexes of the motor.

One of the main problems in design is to select a number of slots with the number of poles given. If the number of slots is determined, we can determine the parameters of the magnetic circuit. Therefore, we did research about fractional slot winding in the case of Ns=3~39, p=1~15, and m=3.

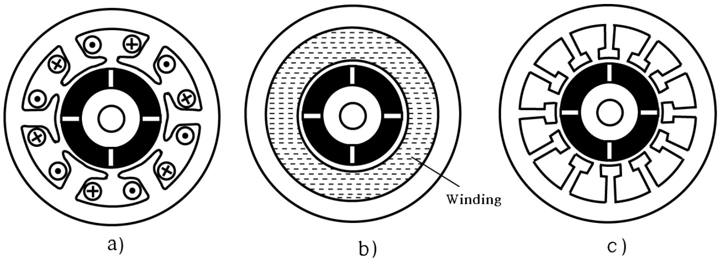


Figure 1. Stator of Brushless DC motor.

The fractional slot must be so designed to meet technical and economical requirements; The Technical requirement is that it must be symmetric 3-phase and the economical requirement is that the winding factor must not be small. Hence, research was done from 2 aspects, technical and economical, separately.

Then we have to determine the number of poles and number of slots taking into account the condition on which cogging torque becomes low, due to the fact that the number of poles and the number of slots make a big difference in the effect of cogging torque.

2. Selecting pole number and number of slots taking into account technical and economic requirements of fractional slot winding

2.1 Selecting the number of poles and number of slots taking technical requirements into account

(1) To make a winding fractional slot, fundamentally $\frac{N_{S0}}{m}$ must be integral.

When N_S, number of slots, p, number of pole pairs ad m, and number of phases are given, we can obtain the G.C.D. of Z and p.

$$N_S = N_{S0}t\,,\; N_P/2 = N_{P0}/2t\,,\;\; t = GCD(N_P, N_S)$$

BLDC Motor has *t* unit windings; a number of slots, a number of pole pairs, and a number of phases which are Z_0, p_0, and m, respectively.

Literature states that a winding can be a fractional slot if $\frac{N_S}{m}$ is integral. However, we have some exceptions in which the winding can't be a fractional slot if $\frac{Z_0}{m}$ is not integral even though $\frac{Z}{m}$ is integral. Table 1 shows such extraordinary cases.

Table 1. Number of pole number of slots which can't make fractional slot winding

2*p*	Ns	2*p*	Ns
6	3,6,12,15,21,24,30,33,39	24	3,6,12,15,21,24,30,33,39
12	3,6,12,15, 21,24,30,33,39	30	3,6,12,15,21,24,30,33,39
18	3,6,9,12,15,18,21,24,30,33,36,39		

Thus we can say that a winding can be a fractional slot only when $\frac{N_{S0}}{m}$ is integral (which means that both $\frac{2p}{d}$, the number of coils per phase and $d \cdot q$, the number of turns per coil are integral).

(2) There must exist some slots, the electrical angles of which are 120° and 240°.

$$\alpha = \frac{360° \cdot N_{P0}}{N_{S0}}\,,\;\; \alpha_i = (i-1)\cdot\alpha \quad (i\text{=1\textasciitilde Ns}_0)$$

where α is the electrical angle of a slot and α_i is the electrical angle of a slot corresponding to the slot number.

For 3-phase winding to make a rotating magnetic field, the phase lag between phases must be 120°exactly.

If this requirement is not satisfied, as shown in Table 2, winding of a phase might be put into slots, but never can windings of other phases be put into slots, leaving 3-phase winding impossible.

Table 2. Number of poles and number of slots that are not satisfied Three-phase symmetric situation

$2p$	N_S	$2p$	N_S
6	6,12,15,21,24,30,33,39	24	21,24,30,33,39
12	12, 15, 21, 24, 30, 33,39	30	24,30,33,39
18	15,18,21,24,30,33,36,39		

Example:

When N_P =6, N_S =30 and m=3 are given

G.C.D. of p and N_S - GCD ($N_P / 2$, N_S) =3

Number of slots and number of pole pairs of unit winding – N p_0=1, $N_{S0} = 10$

The electrical angle between neighboring slots- $\alpha_{\text{slot}} = \frac{360^0 P}{Z} = \frac{360^0 \times 1}{10} = 36^0$

The electric angle between slots

36°, 72°, 108°, 144°, 180°, 216°, 252°, 288°, 324°, 360°,

As you can see, we don't have slots in which the electrical phase lags between 120° and 240°. Thus, we can't put windings of phase B and phase C into slots, resultingly, we can't get a rotating magnetic field.

(3) The number of slots per pole per phase must be $q \geq 0.25$.

According to research on q, number of slots per pole per phase, and three-phase symmetric winding, we can't make a three-phase symmetric winding when q is less than 0.25 but we can when q is greater than 0.25.

Therefore, we study conditions to make three-phase symmetric winding in 2 cases; q<0.25 and $q \geq 0.25$

- In case of $q \geq 0.25$

Although $\frac{N_{S0}}{m}$ is integral, to make a three-phase symmetric winding, the phase lag between phases must be 120°. When q is greater than 0.25, there must exist slots in which phase lags between 120° and 240° among slots ($i = 1 \sim N_{S0}$).

So we studied whether this condition is satisfied in the case of $q \geq 0.25$.

Table 3 shows the results of the research.

Where $\alpha_{sloti} = 120$ °, slot that electric angle is 120 degree in range of i=1- N_{s0} $\alpha_{sloti} = 240$ °, slot that electric angle is 240 degree in range of i=1- N_{s0}

As shown in Table 3, in case of $q \geq 0.25$, there exist slots, electrical angle of which is 120 degrees and 240 degrees, in the range of i=1~ N_{s0} .

- In case of $q < 0.25$

We did a calculation to obtain slots whose electric angle is between 120° and 240° in the range of i=1~ N_{s0} . Table 4 shows the result of the calculation.

As shown in Table 4, there doesn't exist any slot, the electric angle of which is 120° or 240° in the range of i=1~Ns_0 when the number of slots per pole per phase is $q < 0.25$. Therefore, we can't make a three-phase symmetric winding in this case.

From the table3 and table4, the number of slots per pole per phase must be $q \geq 0.25$ in order to get a three-phase symmetric winding.

Table 3. In case of $q \geq 0.25$

$2p$	index							
	N_S	τ	y	β	q	α_{slot}	Slot number of $\alpha_{sloti} = 120^0$	Slot number of $\alpha_{sloti} = 240^0$
2	3	1.5	1	0.667	0.5	120	2	3
	9	4.5	4	0.889	1.5	40	4	7
	15	7.5	7	0.933	2.5	24	11	6
	21	10.5	10	0.952	3.5	17.14	8	15
	27	13.5	13	0.963	4.5	13.33	10	19
	33	16.5	16	0.97	5.5	10.9	12	23
	39	19.5	19	0.974	6.5	9.23	14	27
4	3	0.75	1	1.333	0.25	240	3	2
	6	1.5	1	0.667	0.5	120	2,5	3,6
	9	2.25	2	0.889	0.75	80	6	4
	15	3.75	4	1.067	1.25	48	11	6
	18	4.5	4	0.889	1.5	40	4,13	7,16
	21	5.25	5	0.952	1.75	34.28	15	8
	27	6.75	7	1.037	2.25	26.67	19	10
	30	7.5	7	0.933	2.5	24	6,21	11,26
	33	8.25	8	0.97	2.75	21.82	23	12
	39	9.75	10	1.026	3.25	18.46	27	14
6	9	1.5	1	0.667	0.5	120	2,5,8	3,6,9
	27	4.5	4	0.889	1.5	40	4,13,22	7,16,25
8	6	0.75	1	1.333	0.25	240	3,6	2,5
	9	1.125	1	0.889	0.375	160	4	7
	12	1.5	1	0.667	0.5	120	2,5,8,11	3,6,9,12
	15	1.875	2	1.067	0.625	96	6	11
	18	2.25	2	0.889	0.75	80	7,16	4,13
	21	2.625	3	1.143	0.875	68.57	8	15
	27	3.375	3	0.889	1.125	53.3	10	19
	30	3.75	4	1.067	1.25	48	11,26	6,21
	33	4.125	4	0.97	1.375	43.63	12	23
	36	4.5	4	0.889	1.5	40	4,13,22	7,16,25
	39	4.875	5	1.026	1.625	36.92	14	27
10	9	0.9	1	1.111	0.3	200	7	4
	12	1.2	1	0.833	0.4	150	9	5
	15	1.5	1	0.667	0.5	120	2,5,8,11,14	3,6,9,12,15
	18	1.8	2	1.111	0.6	100	13	7
	21	2.1	2	0.952	0.7	85.7	15	8
	24	2.4	2	0.833	0.8	75	17	9
	27	2.7	3	1.111	0.9	66.67	19	10
	33	3.3	3	0.909	1.1	54.54	23	12
	36	3.6	4	1.111	1.2	50	25	13
	39	3.9	4	1.026	1.3	46.15	27	14
12	9	0.75	1	1.333	0.25	240	3,6,9	2,5,8
	18	1.5	1	0.667	0.5	120	2,5,8,11,14,17	3,6,9,12,15,18
	27	2.25	2	0.889	0.75	80	7,16,25	4,13,22
14	12	0.857	1	1.167	0.286	210	5	9
	15	1.071	1	0.933	0.357	168	6	11
	18	1.286	1	0.778	0.429	140	7	13
	21	1.5	1	0.667	0.5	120	2,5,8,11,14,17,20	3,6,9,12,15,18,21
	24	1.714	2	1.167	0.571	105	9	17

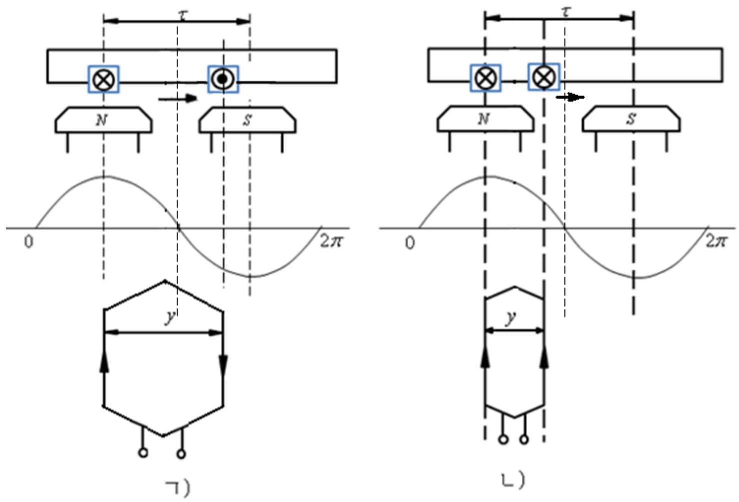
	27	1.929	2	1.037	0.643	93.33	10	19
	30	2.143	2	0.933	0.714	84	11	21
	33	2.357	2	0.848	0.786	76.36	12	23
	36	2.571	3	1.167	0.857	70	13	25
	39	2.786	3	1.077	0.929	64.6	14	27
16	12	0.75	1	1.333	0.25	240	3,6,9,12	2,5,8,11
	15	0.938	1	1.067	0.313	192	11	6
	18	1.125	1	0.889	0.375	160	4,13	7,16
	21	1.313	1	0.762	0.438	137.24	15	8
	24	1.5	1	0.667	0.5	120	2,5,8,11,14,17,20,23	3,6,9,12,15,18,21,24
	27	1.688	2	1.185	0.563	106.67	19	10
	30	1.875	2	1.067	0.625	96	6,21,	11,26
	33	2.063	2	0.97	0.688	87.27	23	12
	36	2.25	2	0.889	0.75	80	7,16,25,34	4,13,22,31
	39	2.438	2	0.821	0.813	73.84	27	14
18	27	1.5	1	0.667	0.5	120	2,5,8,11,14,17,20,23,26	3,6,9,12,15,18,21,24,27
20	15	0.75	1	1.333	0.25	240	3,6,9,12,15	2,5,8,11,14
	18	0.9	1	1.111	0.3	200	7,16	4,13
	21	1.05	1	0.952	0.35	171.42	8	15
	24	1.2	1	0.833	0.4	150	9,21	5,17
	27	1.35	1	0.741	0.45	133.33	10	19
	30	1.5	1	0.667	0.5	120	2,5,8,11,14,17,20,23,26,29	3,6,9,12,15,18,21,24,27,30
	33	1.65	2	1.212	0.55	109.09	12	23
	36	1.8	2	1.111	0.6	100	13,31	7,25
	39	1.95	2	1.026	0.65	92.3	14	27
22	18	0.818	1	1.222	0.273	220	13	7
	21	0.955	1	1.048	0.318	188.57	15	8
	24	1.091	1	0.917	0.364	165	17	9
	27	1.227	1	0.815	0.409	146.67	19	10
	30	1.364	1	0.733	0.455	142	21	11
	33	1.5	1	0.667	0.5	120	2,5,8,11,14,17,20,23,26,29,32	3,6,9,12,15,18,21,24,27,30,33
	36	1.636	2	1.222	0.545	110	25	13
	39	1.773	2	1.128	0.591	101.53	27	14
24	18	0.75	1	1.333	0.25	240	3,6,9,12,15,18	2,5,8,11,14,17
	27	1.125	1	0.889	0.375	160	4,13,22	7,16,25
	36	1.5	1	0.667	0.5	120	2,5,8,11,14,17,20,23,26,29,32,35	3,6,9,12,15,18,21,24,27,30,33,36
26	21	0.808	1	1.238	0.269	222.85	8	15
	24	0.923	1	1.083	0.308	195	9	17
	27	1.038	1	0.963	0.346	173.33	10	19
	30	1.154	1	0.867	0.385	156	11	21
	33	1.269	1	0.788	0.423	141.8	12	23
	36	1.385	1	0.722	0.462	130	13	25
	39	1.5	1	0.667	0.5	120	2,5,8,11,14,17,20,23,26,29,32,35,38	3,6,9,12,15,18,21,24,27,30,33,36,39
28	21	0.75	1	1.333	0.25	240	3,6,9,12,15,18,21	2,5,8,11,14,17,20
	24	0.857	1	1.167	0.286	210	17	9
	27	0.964	1	1.037	0.321	186.67	19	10
	30	1.071	1	0.933	0.357	168	6,21	11,26
	33	1.179	1	0.848	0.393	152.72	23	12
	36	1.286	1	0.778	0.429	140	7,25	13,31
	39	1.393	1	0.718	0.464	129.23	27	14
30	27	0.9	1	1.111	0.3	200	7,16,25	4,13,22
	36	1.2	1	0.833	0.4	150	9,21,33	5,17,29

Table 4. In case of *q*<0.25

2*p*	Ns	*q*	τ	B	*y*	α_{slot}	Indices Slot number of $\alpha_{sloti} \neq 120°$	Slot number of $\alpha_{sloti} \neq 240°$
10	6	0.200	0.600	1.667	2	300	-	-
14	9	0.214	0.643	1.556	2	280	-	-
16	9	0.188	0.563	1.776	2	320	-	-
20	12	0.200	0.600	1.667	2	300	-	-
22	12	0.182	0.545	1.833	2	330	-	-
	15	0.227	0.682	1.467	1	264	-	-
26	15	0.192	0.577	1.733	2	312	-	-
	18	0.231	0.692	1.444	2	260	-	-
28	15	0.179	0.536	1.867	2	336	-	-
	18	0.214	0.643	1.556	2	280	-	-
30	18	0.200	0.600	1.667	2	300	-	-

2.2 Selecting the number of poles and number of slots taking economic requirements into account

(1) To satisfy the economic requirement of fractional slot winding, the cold pitch factor must be β>0.5.



a) In case of $\beta > 0.5$ b) In case of $\beta < 0.5$

Figure 2. Relationship between coil pitch and electromotive force induced on a turn.

As you can see in Figure 2, the electromotive force of a turn is smaller than that of an effective conductor in b) because emfs of 2 effective conductors are canceled each other while emf of a turn equals the sum of those induced on 2 effective conductors in a)

The winding factor is $k_{w1} = k_{d1} \cdot k_{q1}$. In the case of concentrated winding, the winding factor is $k_{w1} = k_{q1}$ due to the distribution coefficient being $k_{d1} = 1$ and in the case of $\beta = 0.5$, the winding factor is as low as 0.707 due to the winding pitch coefficient $k_{q1} = \sin\frac{\beta\pi}{2}$. If $\beta < 0.5$, the winding factor gets smaller. Hence, to satisfy this economical requirement, the winding pitch factor must be $\beta > 0.5$.

(2) Winding factor must be $k_{w1} > 0.85$.

Although the three-phase symmetric winding condition, winding pitch factor and phase lags between phases are satisfied, the rate of copper utilization becomes too small if the winding factor is $k_w < 0.85$.

For example: 2p=10, N_s=6, ($N_{p0} = 5$, N_{s0}=3, t=2)

$$q = \frac{N_s}{2Pm} = \frac{6}{10\times 3} = \frac{1}{5}$$

$\frac{N_s}{m} = \frac{6}{3} = 2$: integer

$\frac{N_{s0}}{m} = \frac{3}{3} = 1$: integer

The electric angle between next slots

$$\alpha_{slot} = \frac{360^0 \cdot P}{Z} = \frac{360^0 \cdot 5}{6} = 300^0$$

Electric angle between slots

300°, 600°, 900°, 1200°, 1500°, 1800°, 2100°, 2400°, 2700°

coil pitch factor

$$\tau = \frac{Z}{2p} = \frac{6}{10} = 0.6 \qquad y=1$$

Distribution coefficient

$$k_d = \frac{\sin\left(\frac{q_e \cdot \alpha_e}{2}\right)}{q_e \sin\frac{\alpha_e}{2}} = \frac{\sin\left(\frac{1\cdot 60^\circ}{2}\right)}{1\cdot \sin\frac{60^\circ}{2}} = 1$$

$$q_e = q\cdot d = bd + c = 1$$

$$\alpha_e = \frac{60^\circ}{q_e} = 60^\circ$$

Short-pitch factor

$$k_q = \sin\left(\frac{\beta\pi}{2}\right) = \sin\left(\frac{180°\cdot 1.667}{2}\right) = 0.5$$

Winding coefficient $k_w = k_q \cdot k_d = 0.5\times 1 = 0.5$

According to calculation, we can make 3-phase symmetric winding due to that electrical angle of between slots are 120°, 240° and make rotational magnetic field. But the rate of copper utilization is low because winding coefficient is $k_w = 0.5$. Therefore, although symmetrical condition of fractional slot winding and phase lag condition between slots are satisfied, we can't use the number of poles and the number of slots.

So, we recommend not to use winding factor $k_w < 0.85$.

Table 5 shows a number of slots according to the number poles which is $k_{w1} < 0.85$.

Table 5. Np and Ns that satisfy the requirement of winding factor

2p	Index						2p	index					
	Ns	q	τ	β	y	k_w		Ns	q	τ	β	y	k_w
10	6	0.200	0.600	1.667	1	0.5	26	15	0.192	0.577	1.733	1	0.389
14	9	0.214	0.643	1.556	1	0.617		18	0.231	0.692	1.444	1	0.735
16	9	0.188	0.563	1.776	1	0.328	28	15	0.179	0.536	1.867	1	0.199
20	12	0.200	0.600	1.667	1	0.500		18	0.214	0.643	1.556	1	0.617
22	12	0.182	0.545	1.833	1	0.250	30	18	0.200	0.600	1.667	1	0.500
	15	0.227	0.682	1.467	1	0.711							

Thus, a number of poles and number slots have to satisfy both technical and economical requirements of fractional slot winding.

① $\frac{N_{S0}}{m}$, a number of element slots per phase must be integral.

Or number of coils per phase $\frac{2P}{d}$ must be integral and the number of branches per coil $d \cdot q$ must be integral.

② There must exist slots, the electric angle of which is $\alpha_{sloti} = 120^0$, $\alpha_{sloti} = 240^0$ (i=1~Ns_0).

③ The number of slots per pole per phase must be greater than 0.25, viz, $q \geq 0.25$

④ Winding pitch factor must be greater than 0.5, viz, $\beta > 0.5$

⑤ Winding coefficient must be greater than 0.85, viz, $k_w > 0.85$

A number of poles and a number of slots are shown in Table 6 to satisfy the above 5 conditions.

Table 6. Pole number and slot number satisfied the technical and economical requirements of fractional slot winding

$2p$	N_s	$2p$	N_s
2	3, 9, 15, 21, 27, 33, 39	18	27
4	3, 6, 9, 15, 18, 21, 27, 30, 33, 39	20	15, 18, 21, 24, 27, 30, 33, 36, 39
6	9, 27	22	18, 21, 24, 27, 30, 33, 36, 39
8	6, 9, 12, 15, 18, 21, 27, 30, 33, 36, 39	24	18, 27, 36
10	9, 12, 15, 18, 21, 24, 27, 33, 36, 39	26	21, 24, 27, 30, 33, 36, 39
12	9, 18, 27	28	21, 24, 27, 30, 33, 36, 39
14	12, 15, 18, 21, 24, 27, 30, 33, 36, 39	30	27, 36
16	12, 15, 18, 21, 24, 27, 30, 33, 36, 39		

Selection of pole number and slot number considered the effect of cogging torque

In the design of a PM electric machine, one of the most important problems is to decrease cogging torque. Therefore, even in case the technical and economical requirements of fractional slot winding are satisfied, we found that cogging torque is related to a combination of a number of slots and a number of poles.

In some pieces of literature stated that the matching coefficient C_{match} should be small and the period coefficient C_{period} should be big to decrease cogging torque.

The matching coefficient is given

$$C_{\text{match}} = \frac{N_p \cdot N_s}{LCM(N_p, N_s)}$$

The minimum value of C_{match} is;1 when the number of slots is an odd number; and 2 when the number of slots is an even number.

Period coefficient

$$C_{\text{period}} = \frac{N_p}{GCD(N_p, N_s)}$$

In literature they proposed to select a matching coefficient as small as possible and, a periodic coefficient as big as possible, recommending $C_{\text{match}} = 1$ (odd slot), $C_{\text{match}} = 2$ (even slot), and $C_{period} \geq 6$.

Therefore, fractional slot winding must be so designed to satisfy this requirement. Table 7 shows the number of slots corresponding to the number of poles satisfying this condition.

Table 7 shows the number of slots corresponding to the number of poles not only satisfying the technical and economical requirement but also decreasing cogging torque. On the other hand, many other methods are proposed to decrease cogging torque such as reasonable selection of pole arc coefficient, skew slot method, making auxiliary tooth method, and pole skew of rotor method with reasonable design of winding. In designing, when it is difficult to determine the number of slots and number of poles by Table 7, we can use other methods to decrease cogging torque and select the number of poles and number of slots by Table 6.

Table 7. Number of poles and number of slots to decrease cogging torque

$2p$	N_s
8	9,15,21,27,33,39
10	9,21,27,33,39
14	12,15,18,24,27,30,33,36,39
16	15,18,21,27,30,33,39
20	18,21,27,33,39
22	18,21,24,27,30,36,39
26	21,24,27,30,33,36
28	27,30,33,39

For example: in the case of $2p$=8, Ns=12
Element winding Np_0=1, Ns_0=3
Matching coefficient $C_{match} = 4$
Periodic coefficient $C_{period} = 2$

In this case, Ns and $2p$ can’t satisfy the matching coefficient and period coefficient. But when you have to select $2p$=8 and Ns=12 in the design of the iron core dimension of the stator and rotor, we recommend using another effective method for the decrease of cogging torque.

4. Conclusion

This paper analyzed three technical requirements and two economical requirements of fractional pitch winding. For the slot number Ns=3~39, and the pole pair number p=1~15, we have found the number of poles and the number of slots of BLDCM satisfying the requirements. We have summarized the optimal number of poles and a number of slots to decrease cogging torque.

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